High Resolution Seismic Reflection Survey to Image the Top and Bottom of a Shallow Clay Layer at the Memphis Defense Depot, Memphis, Tennessee

by

Richard D. Miller
Jianghai Xia
Jeffrey W. Deane
Joe M. Anderson
David R. Laflen
Patricia M. Acker
Mary C. Brohammer

of the
Kansas Geological Survey
The University of Kansas
Lawrence, Kansas

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Executive Summary

Seismic reflection is a geophysical method that is sensitive to changes in acoustic velocity and/or density in the subsurface. Application of shallow seismic reflection to groundwater, engineering, and environmental problems has been on the increase since the mid-1980s. It is likely, due to the nature of the mission of the 642 acre Defense Depot Memphis, Tennessee (DDMT), that certain items have been spilled, leaked, or disposed of on-site since its establishment in 1942. Shallow seismic reflection was used to identify potential pathways for hydrologic movement of contaminants along and through a drill defined non-permeable clay layer.

The focus of this survey was the northwestern corner of the main facility. The two-dimensional subsurface image generated by the reflection survey extends from the fence on the west to guard shack #15 on the east. A structural low in the confining clay layer separating the Memphis Sand (regional fresh water aquifer) from the overlying unconfined (surface recharge) aquifer has been inferred from several widely spaced boreholes. The seismic survey confirmed the presence of the low and improved the accuracy of the geometries.

The seismic reflection data was interpreted to produce a general geologic cross-section. The cross-section suggests that the drill inferred low in the clay layer is east of the railroad spur. The exact width of the low cannot be determined due to a combination of lack of subsurface coverage and extremely high levels of powerline noise. The bottom of the clay is interpreted at approximately 160 ft. Seismic data suggest that the clay thins to no less than 30 ft on the extreme eastern end of the line. Based on seismic data only, the clay layer seems to be continuous and undulates in thickness from about 70 to 30 ft and in depth between 90 and 130 ft.

Introduction

Fluid movement, both surface and subsurface, at the Defense Depot in Memphis, Tennessee (DDMT) is of interest to the U.S. Army Corps of Engineers (Figure 1). The U.S. Army Engineer Division, Huntsville, through the U.S. Army Engineer Waterways Experiment Station, Vicksburg (WES), initiated a shallow seismic reflection survey to determine lateral continuity and surface topography of a clay layer previously encountered during evaluation drilling. A small feasibility study was undertaken by WES to determine the potential of the technique at this site (Miller, 1993). Preliminary analysis suggested it should be possible to image at least the top of the clay. Considering the findings of the feasibility study, and with the alternative being grid drilling, approval was granted for a 1200 ft Common Depth Point (CDP) or Common Mid-Point (CMP) production line between guard shack #15 (located in the northwest corner of the main installation) and the west boundary fence.

The proposed targets were the top and bottom of a clay layer at depths between 80 and 150 ft overlying the Memphis Sand (based on a cross-section derived from drill records) and any potentially hydrologically significant layers between the ground surface and the base of the Memphis Sand. The primary goal was to determine the overall thickness of the clay and determine if it represents a non-permeable interface between the ground surface and the Memphis Sand. Lateral discontinuity of the clay from either erosion or faults/joints was of particular interest.

The subsurface geology interpreted from borehole data should be very conducive to shallow reflection techniques (Steeples and Miller, 1990). The existing borehole data suggest a clay layer about 60 to 80 ft thick and 80 ft deep on the west end of the seismic line. The top of the water table is interpreted to follow the contours of the clay and is about 5 to 10 ft above the clay surface. A second borehole near the east end of the line encountered the clay layer at over 140 ft of depth with the water table directly above the clay. These conditions and subsurface geometries should represent an ideal application of the technique (Miller et al., 1989; Miller et al., 1990; Goforth and Hayward, 1992; Merey et al., 1992).

A feasibility study conducted by WES during September of 1993 was successful in defining realistic expectations and effort necessary for shallow seismic reflection to be effectively used at DDMT (Miller, 1993). Near-surface conditions, and to a lesser degree equipment available, limited the overall quality of the test data. The gravel surface overlaying compacted clay fill drastically attenuated signal from the sledge hammer source. Subsurface detonation of explosives was not possible during the feasibility study due to the safety risk associated with the loose gravel surface and the on-site ability to properly prepare shotholes. Receiver coupling was compromised by both short spikes and abundance of loose gravel fill. On-site analysis of the test data was not sufficiently conclusive to justify commencing the production portion of the survey at that time. Reflecting events revealed during post-acquisition analysis, subdued by noise, were very sensitive to geophone and source coupling. With the prospects of useful data (with improved conditions and specific equipment), the Kansas Geological Survey (KGS) proposed to acquire the production portion of the project using specially designed equipment and particular site preparations (geophone and source trench).

The survey was conducted on 24 and 25 January 1994. The project consisted of several walkaway noise tests (tests designed to help maximize parameters and equipment for specific conditions) and a 160 shotpoint, nominal 24-fold CDP line (Figure 2). The surface conditions required the opening of a 3 ft wide 1.5 ft deep trench across the gravel storage yard for the receivers and a secondary trench 8 in deep and 1 ft wide for the source. The source was detonated in and the receivers were planted into the compacted clay fill that underlay the gravel surface cover west of the railroad spur (Figure 2). The ground surface was damp and there were several small pools of water in the geophone trench during the first day of shooting (the moisture in the trench improved coupling and reduced attenuation). The walkaways and the first 60 shotpoints of data were collected on 24 January, with the remaining 100 shotpoints of the CDP line collected on 25 January. The night of 24 January a significant rainfall was recorded, filling the geophone and source trench. The powerline-induced noise (60 Hz, 120 Hz, 180 Hz, etc.) was visible on recorded data on 24 January, but due to an increase in the electrical conductivity of the soils after the rain, the powerline noise was overwhelming on 25 January. The increase in recorded powerline noise was the primary factor that hampered the overall quality of the recorded data on the east end of the line.

Data Acquisition

Data for this study were acquired on a 48-channel EG&G Geometrics 2401x seismograph. The seismograph amplifies, filters (analog), digitizes the analog signal into a 15-bit word, and stores the digital information in a demultiplexed format.

Analog filters have an 18 dB/octave rolloff from the selected -3 dB points. The 1/2 ms sampling interval resulted in a 2000 Hz sampling frequency for a record length of 500 msec and a 1000 Hz Nyquist frequency. A 250 Hz high-cut filter with a 24 dB/octave rolloff acted as an anti-alias filter and to reduce wind noise and higher modes of 60 Hz powerline noise. The Geometrics 2401x is a floating-point seismograph. The dynamic range of the seismograph was more than adequate to record high-quality reflection information at this site in the presence of source-generated and cultural noise.

Walkaway data were acquired with a variety of field parameters, offsets, and source energy in an attempt to optimize the production data. Direct wave, refractions, ground roll, reflections, and air-coupled wave can all be identified best on walkaway data recorded with offsets less than 200 ft. The sources for the testing included the 8- and 12-gauge auger gun (Healey et al., 1991). The receivers for the entire study were Mark Products L-28E 40 Hz geophones wired in series with three geophones per string. The station spacing for the walkaways was 4 ft. The resulting walkaway spreads possessed 96 traces with offsets ranging from 8 ft to 196 ft (source locations off both ends of the line were occupied).

The production portion of the survey involved 160 shotpoints along a single east/west line roughly parallel to the north fence with 8 ft station spacings (Figure 2). The source for the CDP data was the 8-gauge auger gun. The three geophones were placed in a 3 ft in-line array to help attenuate source-generated air coupled wave. The seismograph was configured to focus on reflections from the upper 250 msec with average velocities from 1200 to 6000 ft/sec. The pre-amplified spectra was shaped with 50 Hz analog low-cut filters, in an attempt to enhance the higher frequency components of the recorded energy. Emphasis on pushing the high side of the spectra was necessary to separate the reflections from the top and bottom of the 80 ft clay.

Data Processing

Data processing was done on an Intel 80486-based microcomputer using *Eavesdropper*, a set of commercially available algorithms. The processing flow was similar to those used in petroleum exploration (Table 1). The main distinctions relate to the conservative use and application of correlation statics, precision required during velocity and spectral analysis, and extra care during muting operations.

For most basic shallow, high-resolution seismic reflection data the processing steps/operations are a simple scaling down of established petroleum-based processing techniques and methods. However, processes such as deconvolution have basic assumptions (Yilmaz, 1987) that are violated by most shallow data sets. For this data set a second zero crossing auto predictive deconvolution partially suppressed the reflection wavelet. Migration is another operation that, due to non-conventional scaling (vertical and/or horizontal), many times may appear to be necessary when in actuality geometric distortion may be simple scale exaggeration (Black et al., 1993). The subtle improvement on this data set observed when both deconvolution and f-k migration were applied allowed a more complete interpretation. Processing/ processes used on data for this report has/have been carefully executed with no *a priori* assumptions and with care not to create anything during a processing operation that was not present before.

To reduce the effects of the powerline noise and to attenuate ground roll, air-coupled wave, and refracted arrivals, f-k filtering and digital bandreject filtering were evaluated. F-k filtering (also referred to as velocity filtering, slope filtering, pie filtering) successfully removed linear arrivals and effectively narrowed the bandwidth of the reflection information. The narrowing of the bandwidth resulted in the ringy appearance of the reflection wavelets. This narrowing of the wavelets was so dramatic that the reflections interpreted from the top and bottom of the clay began to interfere, indicative of reduced resolving power.

Results

Unequivocal identification of reflection energy on field files is essential for accurate interpretation of CDP stacked sections. A few of the digitally filtered field files acquired during the production portion of the survey have reflection events identifiable between 70 and 150 msec. The reflections have a dominant frequency of approximately 80 Hz and an apparent normal moveout (NMO) velocity of approximately 2750 ft/sec. These would result in an approximate depth to the reflector of between 100 and 180 ft. The signal-to-noise ratio on the raw field files is sufficient to confidently identify reflections on most files from the west end of the line, but the 60 Hz noise (180 Hz) is sufficiently strong that most longer-offset traces are saturated with noise.

Analysis of processed field files improves confidence in interpretations of CDP stacked sections. The variability in data quality is evident on amplitude adjusted field files from across the line (Figure 3). The coherent events identifiable on some of the filtered files possess an arrival pattern consistent with the classic hyperbolic moveout of a reflection (Figure 4). These interpreted reflection arrivals allow significant confidence in interpreting the CDP stacked section. It is still prudent to practice care and a conservative approach to interpretations of coherent energy on stacked data.

Coherent events can be interpreted across the CDP stacked section (Figure 5). The stacked section possesses nominal 24 CDP fold redundancy as a result of the 48-channel recording system and the split-spread recording geometry. The fold drop near the ends of the lines inhibits high confidence in interpretations within 20 CDP of the line ends. There are two correlatable events between 60 and 130 msec. The narrow bandwidth of the reflection wavelet is evidenced by the very cyclic appearance of the stacked reflections. The resolving power (i.e., dominant frequency and bandwidth) of the CDP stacked sections are reduced by the near-surface conditions at this site.

The dominant frequency of most recorded reflection energy is between 50 and 100 Hz. The stacking velocity ranged from 2000 to 3500 ft/sec. The stacked section provides adequate resolution potential and excellent coherency over the west half of the line. The extremely high levels of powerline noise inhibited confident interpretations on the east portion of the line. Severe muting and advanced post-stack processing (i.e., f-k migration and deconvolution) helped to enhance the interpretation along the entire line (Figure 6).

The CDP stacked section possesses two interpretable reflection (Figure 6). The shallowest reflection (75 to 80 msec) is approximately 90 to 100 ft deep (based on NMO velocities) on the west end of the line. The second reflection (115 msec) is approximately 160 ft deep (again based on NMO velocities) on the west end of the line. From CDP 400 to 500 the increased powerline noise is evident. Interpreting reflections in this window is difficult, but sufficient coherency exists to suggest reflector geometry. The deeper event is most likely the base of the clay layer, while the shallower event could be either the top of the clay or the water table that according to drilling is coincident with the top of clay. If the clay layer is defined by the two interpreted reflecting events, the clay layer gradually thickens from the west end of the line to about CDP 400, where the thinning suggested by local boreholes begins to become evident.

The apparent time structure of these reflecting events is probably influenced around CDP 360 by near-surface irregularities in velocity (Figure 6). The effect of the variable near-surface is the synclinal feature between CDP 330 and 400. The exact geometric duplication of the apparent structure on both events is strong evidence to support a velocity anomaly rather than true structure. Some indications of a near-surface velocity anomaly are evident in refracted arrivals on processed field files. The change in velocity above the clay (assuming the shallowest reflection is from the top of clay) as evidenced by this depression could be indicative of change in the water table elevation. Removing the effects of the proposed velocity anomaly would result in a very uniform geologic cross-section (Figure 7b). The suggestion that this structure is a velocity artifact and not real is a deduction and has no ground truth support. There is a chance that this structure is real, in which case the geologic cross-section would be very similar to the interpreted seismic section (Figure 7a). Several possible yet unlikely explanations for the apparent mimicked structure on both reflections include subsidence, faulting, folding, and coincidental erosion. The syncline is most likely a velocity artifact.

Conclusions

Seismic reflection effectively imaged the top and bottom of the confining clay approximately 80 to 160 ft deep. The high levels of cultural noise and fill material covering the entire site had a detrimental effect on the overall data quality. The heavily traveled road, power lines, noise from machinery, surface obstructions, and fill material negatively affected the resolution potential of data collected at this site. The dramatic change in near-surface materials east of the railroad decreased the horizontal consistency of the stacked data. The dominant frequency of body wave energy and the narrow band nature (very cyclic, ringy with attempts to shape the spectrum) of most arrivals on field files is consistent with this very attenuative near-surface. The potential resolving power of the technique at this site could increase by as much as double if the near-surface (i.e., upper 5 to 10 ft) were native materials. The clay layer appears to thin to less than 30 ft beneath station 250 but does not truncate.

The clay layer does not appear to truncate within the subsurface area imaged by this seismic reflection survey. From station 200 west the clay layer possesses apparent westward dip and a consistent thickness. East of station 200 the clay lens begins to converge, thinning to no less than 30 ft around station 260. This convergence is the result of an increase in depth to the top of the clay while the depth to the basal contact of the clay with the Memphis Sand appears to be relatively consistent across the entire line. If the water table is perched 5 to 10 ft above the clay across the expanse of this line, identification of the geologic/hydrologic interface responsible for the event is not critical. However, if the shallowest reflection is the water table and the top of the clay significantly diverges from the water table on the eastern end of the line, confidence in the continuity of the clay would decrease. Even with the poor data quality at the eastern end, a strong case can be made for a thinning clay without truncation. Verification of this interpretation is appropriate and very plausible with a minimal drilling effort.

Recommendations

Two confirmation boreholes with velocity check shots would allow full confidence in the interpretation of the seismic reflection data. A borehole at station 180 (to verify/refute the interpreted velocity anomaly) and another at station 250 (to verify the interpreted increase in depth to the top of clay) and the associated uphole surveys would provide ground truth for the interpretative geologic cross-section. In both boreholes the thickness of the perched water table and its associated depth would be critical to confirming the preferred interpretation. If the borehole and velocity complement the CDP stacked section, a second seismic line starting near CDP 160 and extending beyond the guard shack on the east should resolve the channel inferred from drilling and partially imaged on the eastern end of the seismic line.

References

Black, R.A., D.W. Steeples, and R.D. Miller, 1993, The utility of migration on shallow seismic reflection data: *Geophysics*, v. 59, n. 3, p. 402-410.

Goforth, T., and C. Hayward, 1992, Seismic reflection investigations of a bedrock surface buried under alluvium: *Geophysics*, v. 57, n. 9, p. 1217-1227.

Healey, J., J. Anderson, R.D. Miller, D. Keiswetter, D.W. Steeples, and B. Bennett, 1991, Improved shallow seismic-reflection source: building a better Buffalo [Exp. Abs.]: Soc. Explor. Geophys. v. 1, p. 588-591.

Merey, C., R.D. Miller, E.J. Ticken, and J.S. Lewis, 1992, Hydrogeologic characterization using a shallow seismic reflection survey at Fort Ord, California [Exp. Abs.]: Soc. Explor. Geophys., v. 1, p. 370-373.

Miller, R.D., 1993, Feasibility of seismic reflection to image the top and bottom of an 80 to 150 ft deep clay layer at the Memphis Defense Depot: Kansas Geological Survey Open-file Report 93-57.

Miller, R.D., D.W. Steeples, R. Hill, and B. Gaddis, 1990, Identifying intra-alluvial and bedrock structures shallower than 30 meters using seismic-reflection techniques: Soc. Explor. Geophys. volumes on Geotechnical and Environmental Geophysics, Stan Ward, ed., *Volume 3: Geotechnical*, p. 89-98.

Miller, R.D., D.W. Steeples, and M. Brannan, 1989, Mapping a bedrock surface under dry alluvium with shallow seismic reflections: *Geophysics*, v. 54, n. 12, p. 1528-1534.

Steeples, D.W., and R.D. Miller, 1990, Seismic-reflection methods applied to engineering, environmental, and ground-water problems: Soc. Explor. Geophys. volumes on Geotechnical and Environmental Geophysics, Stan Ward, ed., *Volume 1: Review and Tutorial*, p. 1-30.

Yilmaz, O., 1987, Seismic data processing; S. M. Doherty, Ed.; *in* Series: Investigations in Geophysics, no. 2, Edwin B. Neitzel, Series Ed.: Soc. of Explor. Geophys., Tulsa, Oklahoma.

TABLE 1

Processing flow

format from SEG2 to KGSEGY
preliminary editing (automatic bad trace edit with 10 msec noise window)
trace balancing (150 msec window)
first arrival muting (detailed trace by trace mutes based on arrival identification)
surgical muting (removal of air coupled wave based on trace-by-trace arrival)
assign geometries (input source and receiver locations)
sort into CDPs (re-order traces in common midpoints)
velocity analysis (whole data set analysis on 100 ft/sec increments)
spectral analysis (frequency vs amplitude plots)
NMO correction (station dependent ranging from 2,250 to 3,500 ft/sec)
digital filtering (bandpass 40-80 200-275)
secondary editing (manual review and removal of bad or noisy traces)
CDP stack
amplitude normalization (AGC 50 msec with 20 msec delay)
display

deconvolution (second zero crossing predictive)
f-k migration (2,500 ft/sec constant velocity)
bandpass filter (30-60 180 250)
AGC scale (100 msec window)
display

Table 1. Processing flow for CDP stacked data. Parameters were determined by analysis for each prior step as well as through iterative analysis of particular operations.

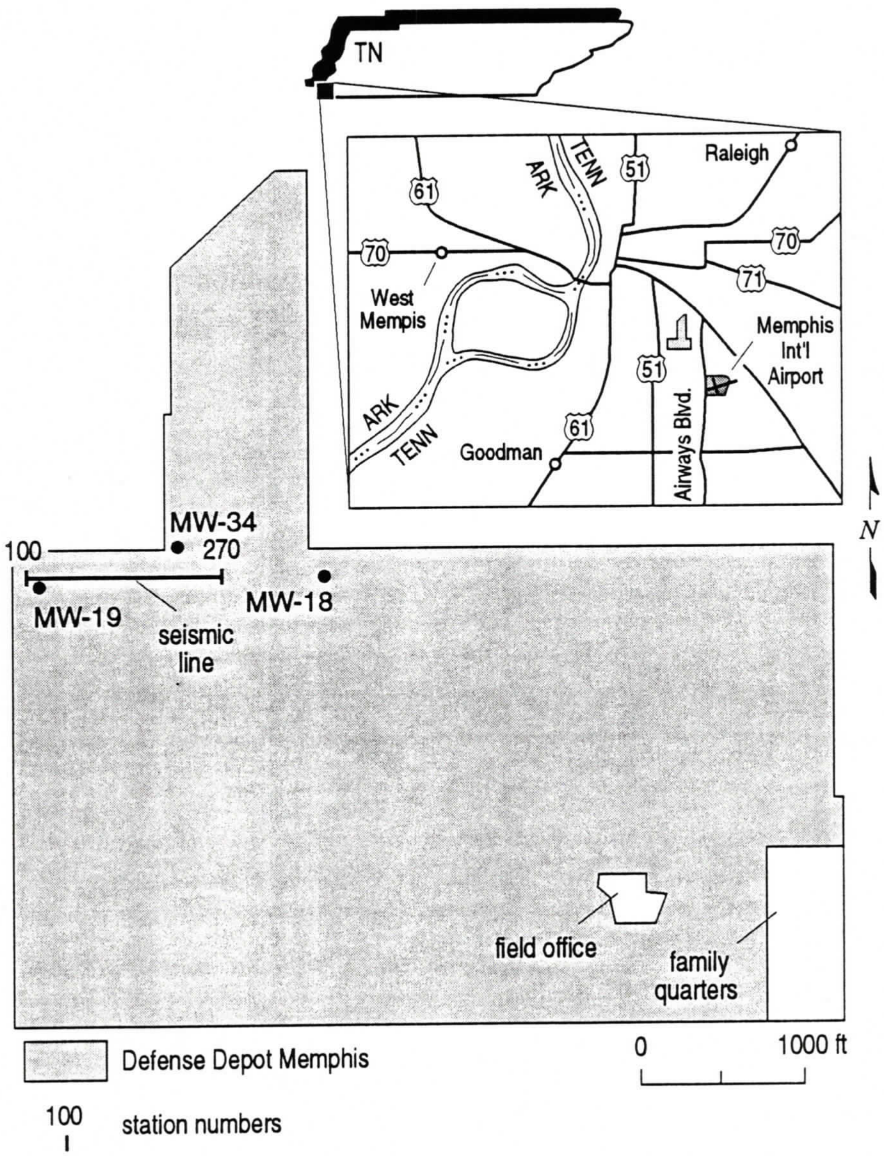

Figure 1. Location map indicating relative location of the seismic profile at Defense Depot Memphis, Tennessee (DDMT) to previous boreholes and with respect to the state and city.

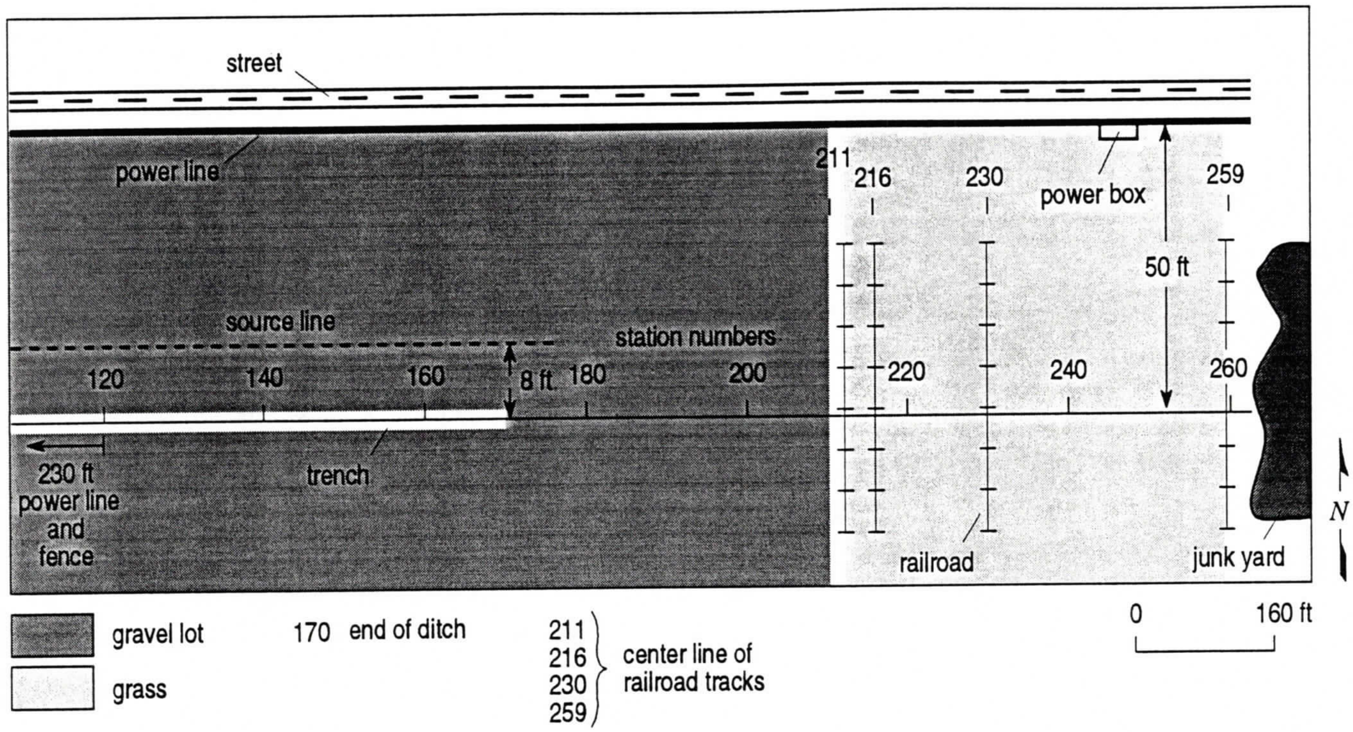

Figure 2. Site map with surface station locations relative to surface landmarks at DDMT.

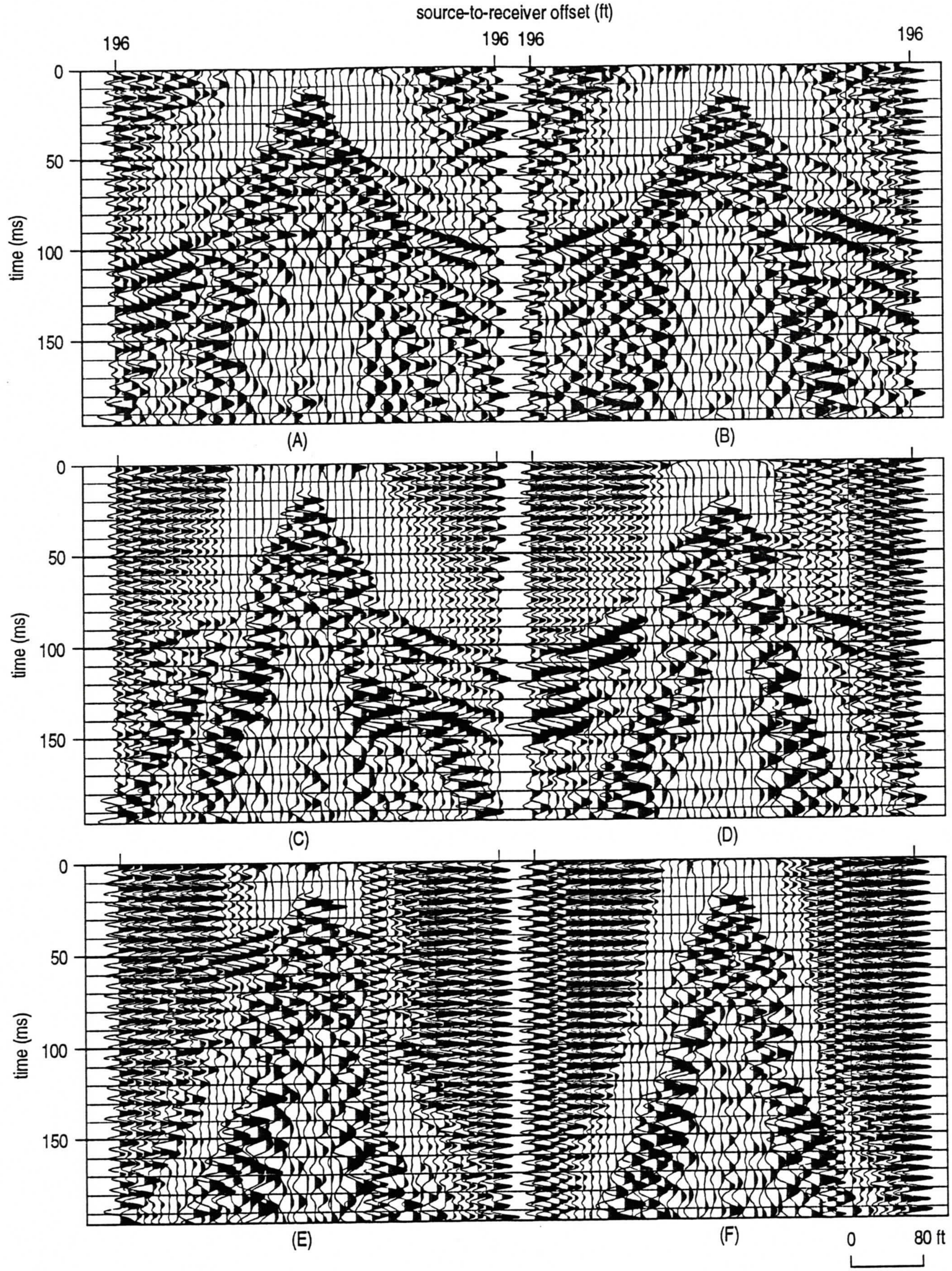

Figure 3. AGC scaled field files from across the seismic line. Field file (a) is from the western end while field file (f) is from the eastern end of the line. The reflection from the top of clay is evident on field files (a) and (b). The increase in powerline noise is evident on files (d), (e), and (f).

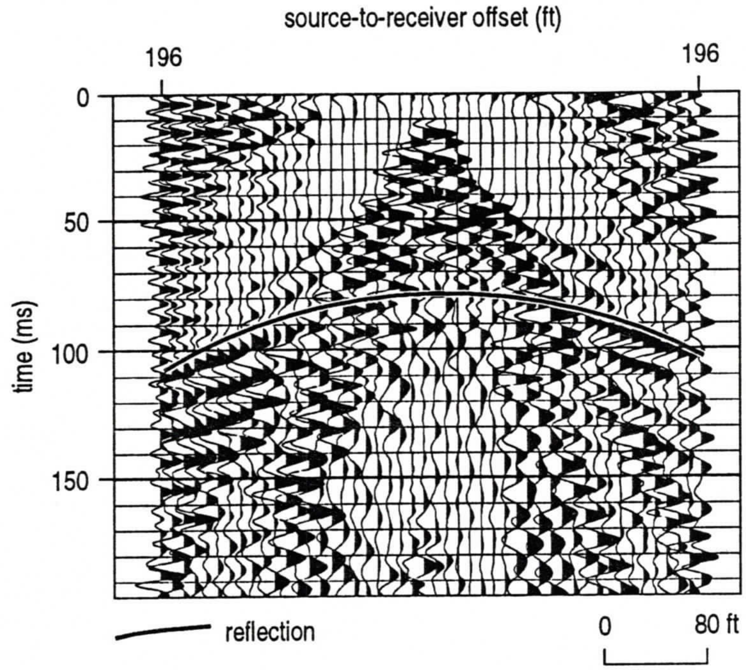

Figure 4. The reflection event on the AGC scaled field file (a) from Figure 3 correlates very well to an idealized reflection hyperbola representing a velocity of 2500 ft/sec.

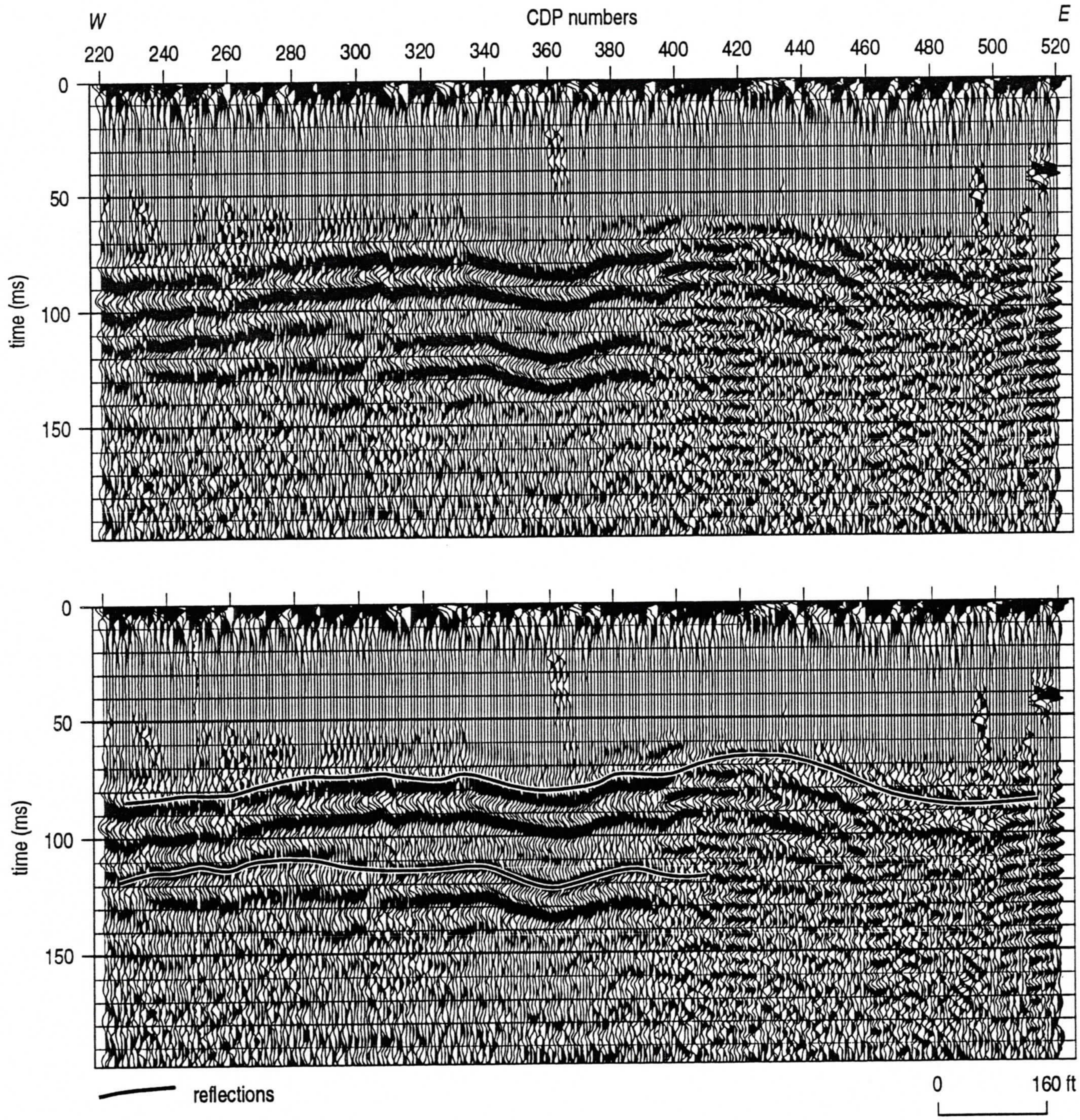

Figure 5. 24-fold CDP stacked section (a) with interpretation (b) of the top and bottom of the clay layer. The cyclic nature of the stacked reflections are indicative of the narrow bandwidth of the reflected wavelets. Interpretation of the basal contact cannot be done with confidence on the east end of the line due to the extreme interference from powerline noise.

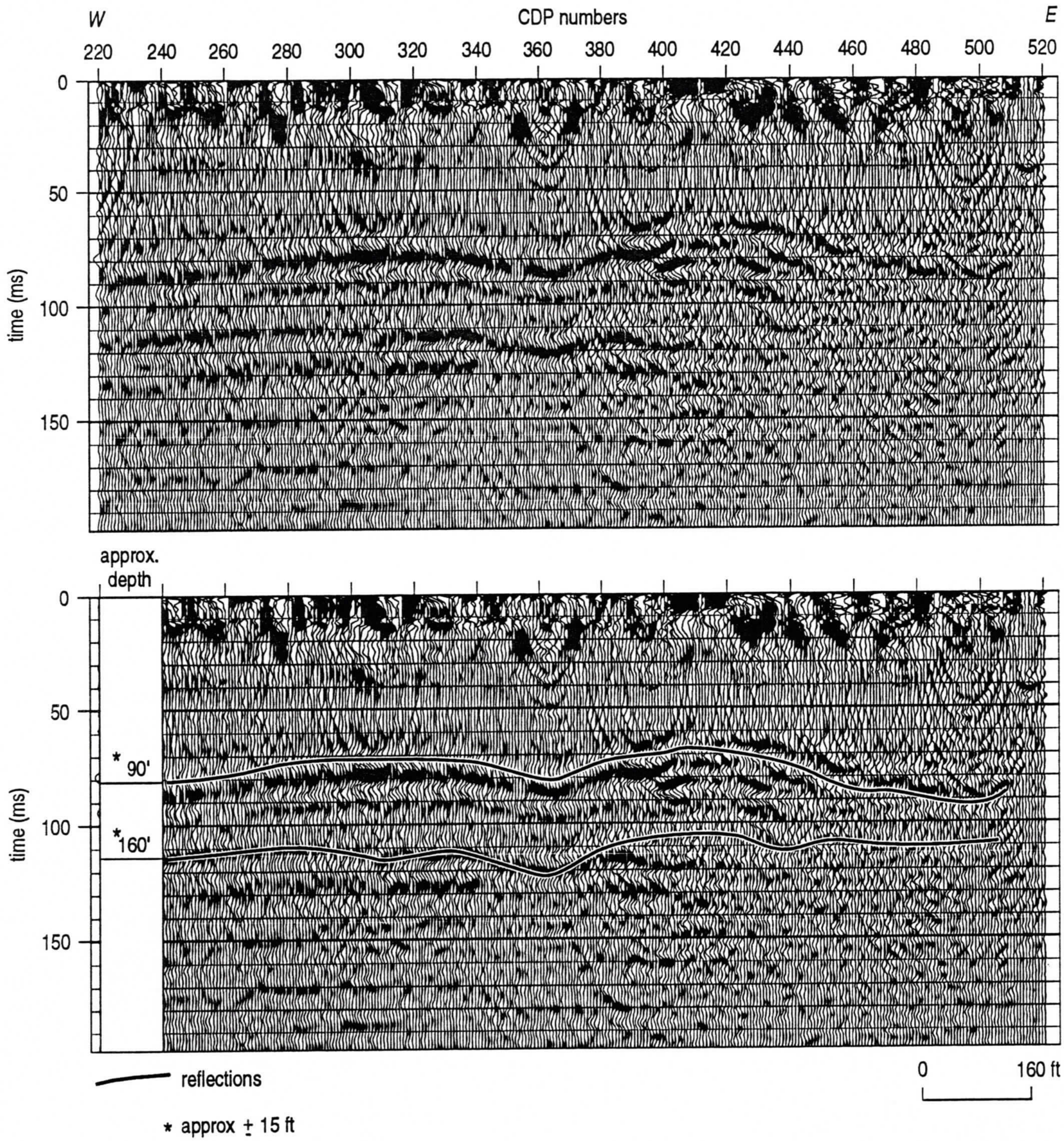

Figure 6. Deconvolution and f-k migration of the CDP stacked section (Figure 5) was effective in suppressing the reflection wavelet (a) and allowed the continuation of the interpretation (b) of the basal reflection on the east end of the line. The variable time separation between the two interpreted reflection events supports separate reflections and reduces the possibility of the deeper event being some form of multiple.

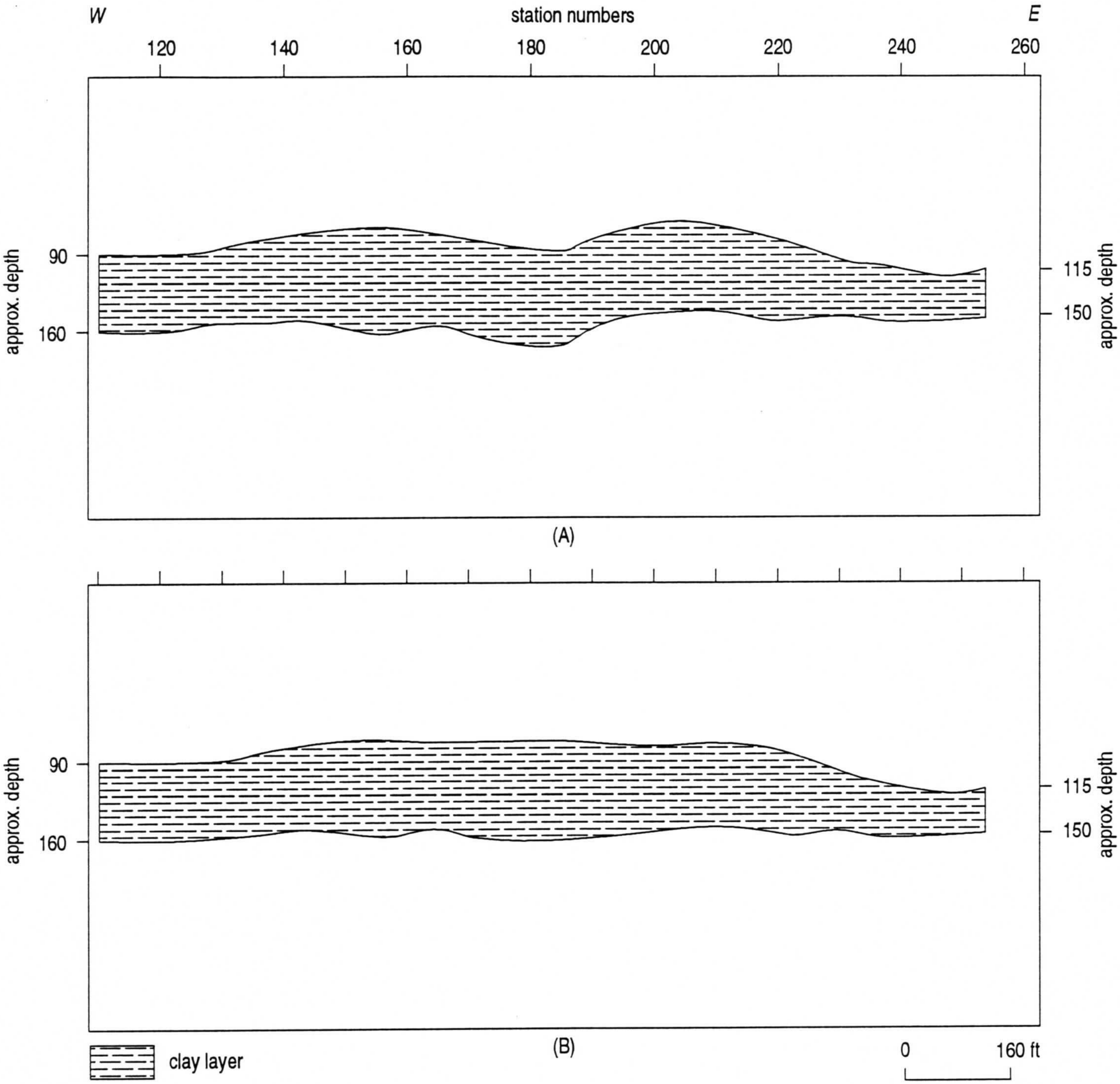

Figure 7. Interpretive cross-section derived from the seismic reflection section with the clay identified based on drill data. The cross-section (a) based purely on the time section (Figure 6) allows identification of the channel feature inferred from drilling near the east end of the line. If the synclinal feature around 180 (a) is the result of a velocity anomaly, a much more uniform and geologically favorable cross-section (b) results when it is compensated for.